Theory Lessons from the First LHC Runs at O(1 TeV)

Peter Skands (CERN PH-TH)

Disclaimer

- Impossible to cover everything
- *Focus* on important outstanding questions which could be settled by early LHC measurements at 900 and 2360 GeV
- Note that, for most of them, this is our *only* chance to settle these questions
- The answers are crucial to improving our physics models

Monte Carlos and Precision

- A Good Physics Model gives you
  - Reliable calibrations for both signal and background (e.g., jet energy scales)
  - Reliable corrections (e.g., track finding efficiencies)
  - Background estimates with as small uncertainty as possible (fct of both theoretical accuracy and available experimental constraints)
  - Reliable discriminators with maximal sensitivity to New Physics

Count what is Countable

Measure what is Measurable

(and keep working on the beam)

G. Galilei

Amplitudes
Monte Carlo
Resummation
Strings
...

Theory

Feedback Loop

Experiment

Hits
0100110
GEANT
B-Field
....

Theory worked out to
Hadron Level
with acceptance cuts
(~ detector-independent)

Measurements corrected to
Hadron Level
with acceptance cuts
(~ model-independent)

If not worked out to hadron level: data must be unfolded with *someone else's* hadron-level theory

Unfolding beyond hadron level dilutes precision of raw data (Worst case: data unfolded to ill-defined 'MC Truth' or 'parton level')

Constraining Models

- A wealth of data available at lower energies
- Used for constraining ('tuning') theoretical models (E.g., Monte Carlo Event Generators)

Constraining Models

- A wealth of data available at lower energies
- Used for constraining ('tuning') theoretical models (E.g., Monte Carlo Event Generators)

- The low-energy LHC runs give us a *unique chance* to fill in gaps in our knowledge at lower energies
- Which model would you trust more? One that also describes SPS, RHIC, Tevatron, Low-Energy LHC? Or one that doesn't?

Constraining Models

- A wealth of data available at lower energies
- Used for constraining ('tuning') theoretical models (E.g., Monte Carlo Event Generators)

- The low-energy LHC runs give us a *unique chance* to fill in gaps in our knowledge at lower energies
- Which model would you trust more? One that also describes SPS, RHIC, Tevatron, Low-Energy LHC? Or one that doesn't?

But wait ... which gaps?

Charged Multiplicity

- One of the most fundamental quantities to measure
- But fundamental does not imply easy

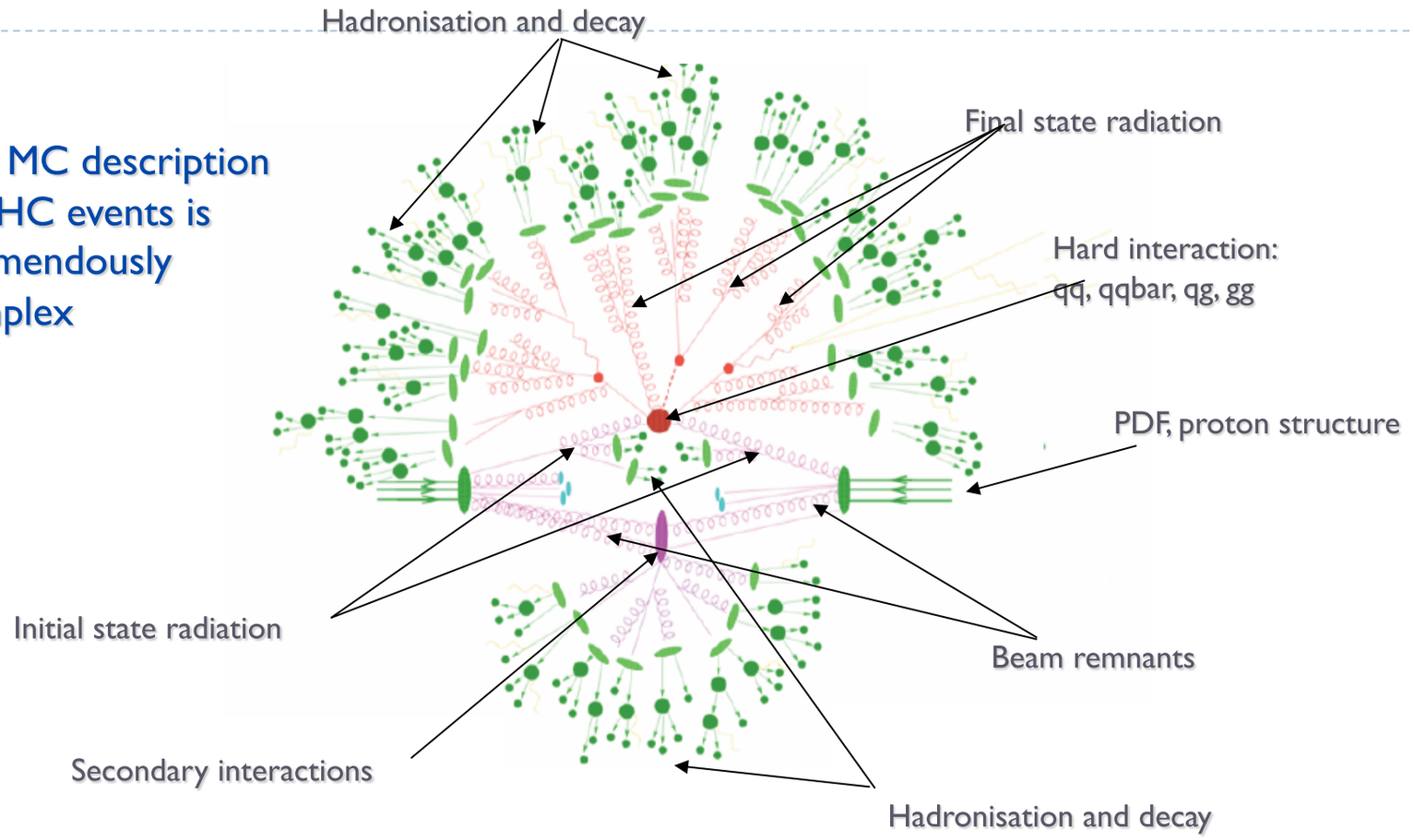
Charged Multiplicity

- One of the most fundamental quantities to measure
- But fundamental does not imply easy
- Complications: Corrections for Trigger Bias, Diffraction, Zero Bin, Long-Lived particles, Extrapolations from raw measurement to: hadron-level (with acceptance cuts) and/or to: hadron-level (full phase space), ...

Dissecting Minimum-Bias

Physics requirements: basics

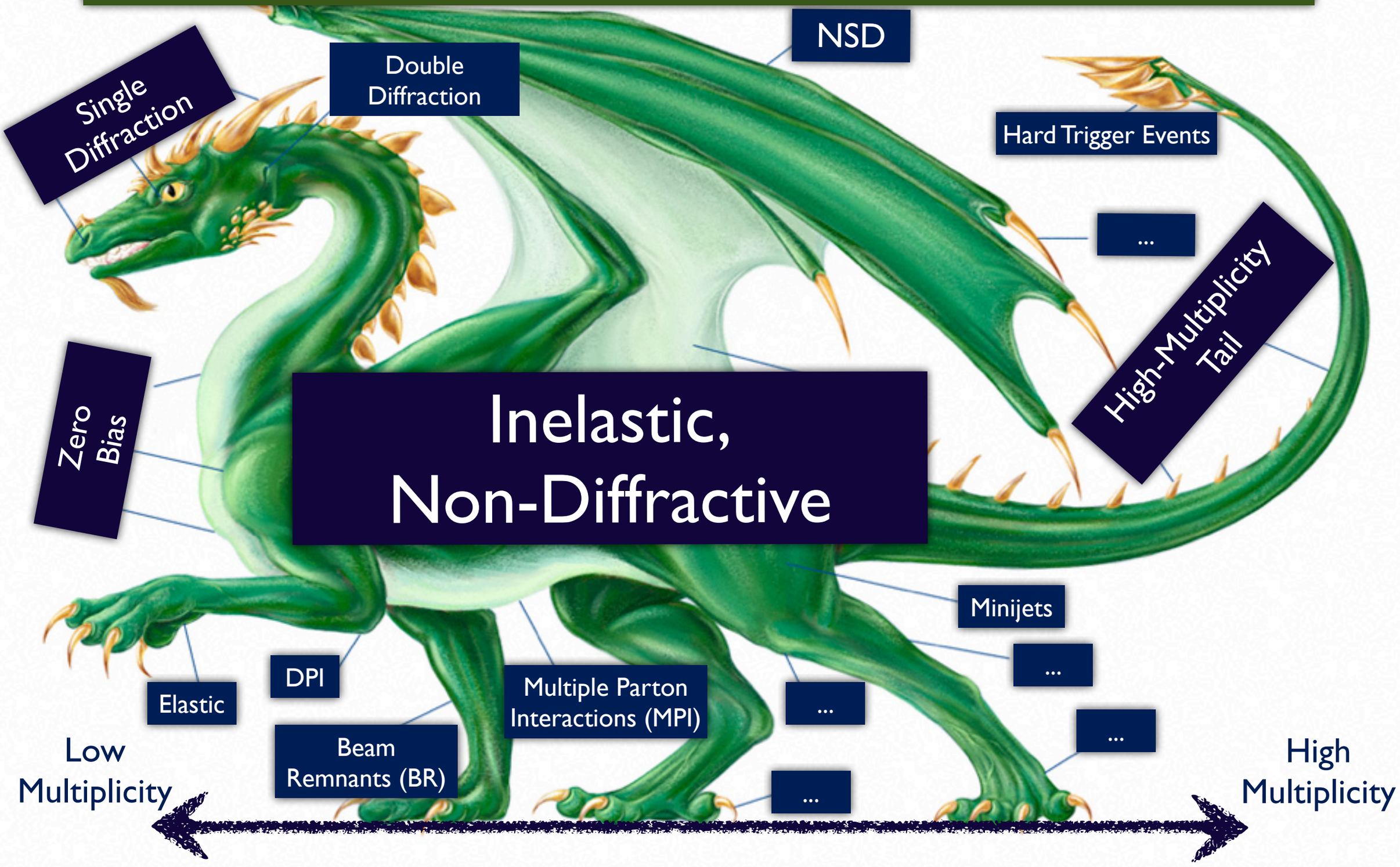
The MC description of LHC events is tremendously complex



This is a schematization to be able to cut down the problem in pieces and model them in a different way. The "pieces" are correlated !

(slide from F. Cossutti (CMS), 7th MCnet Annual Meeting, January 2010)

Dissecting Minimum-Bias



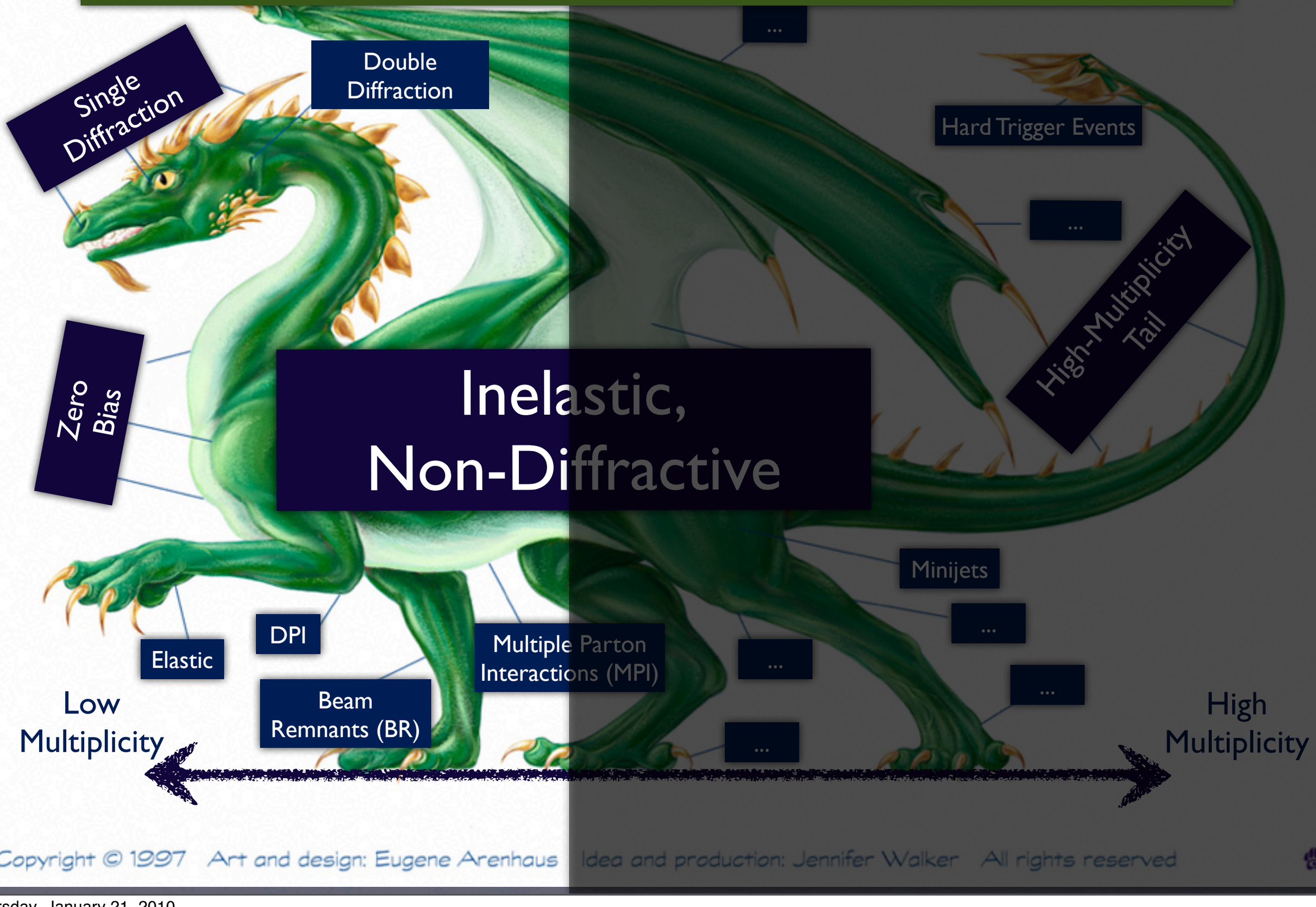
Measured Results

- How to Compare to Older Measurements?
  - Bubble chambers etc extrapolated to full phase space
  - More model-dependent at Tevatron and LHC experiments

Measured Results

- How to Compare to Older Measurements?
  - Bubble chambers etc extrapolated to full phase space
  - More model-dependent at Tevatron and LHC experiments
- How to Compare to Theory?
  - Inelastic > 'NSD' > Inelastic Non-Diffractive, ... ?
  - For all: Define event set in terms of hadron-level cuts
  - Today's theorists not interested in filling up unmeasured region with some model (especially if it is some other guy's model) - Keep main measured result as close to raw acceptance as possible. Extrapolate *only* to do comparisons (inflates uncertainties)

Issues at Low Multiplicity

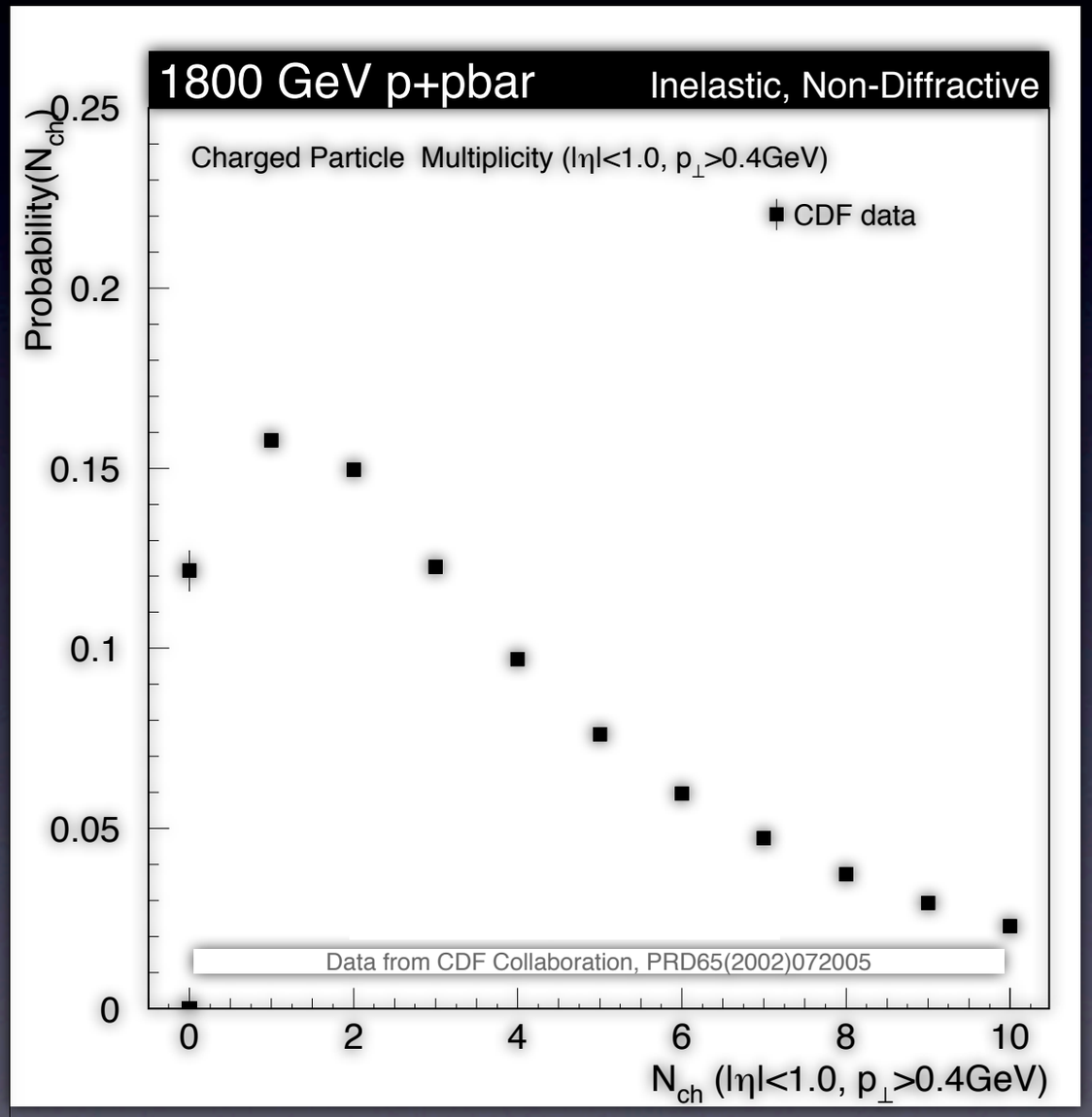


Low Multiplicities: Correcting for Diffraction

- Diffractive processes
  - Large part of total cross section
  - Populate the low-multiplicity bins: lower $\langle N_{ch} \rangle$
  - Characteristic rapidity spectrum with large rapidity gaps: affect $dN_{ch}/d\eta$
  - Impossible to interpret min-bias spectra without knowing precisely how diffraction was treated

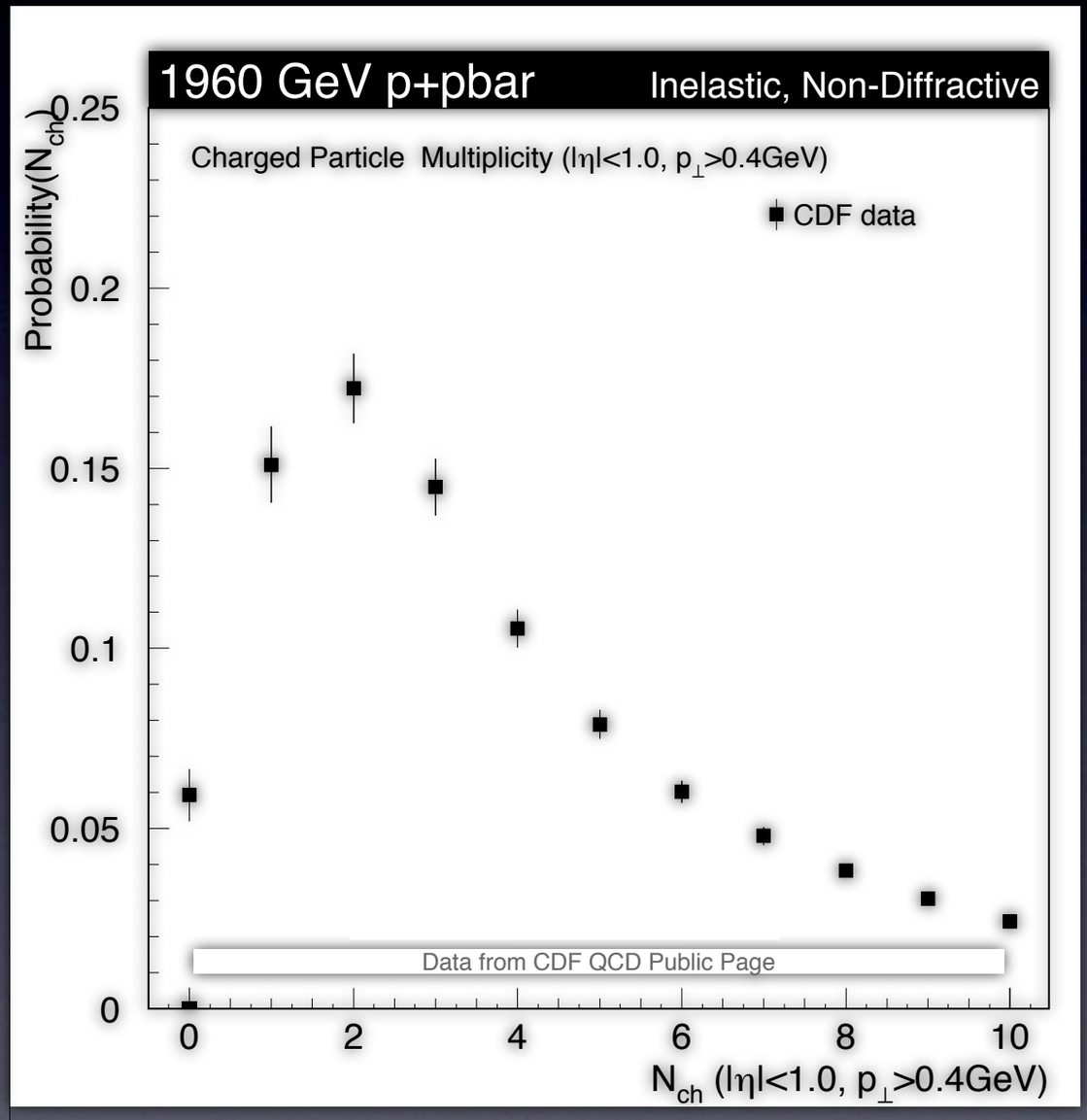
Low Multiplicities: Correcting for Diffraction

- CDF Run-I Data
  - Corrected to pT>0.4 GeV instead of full PS: less model dependence
  - First few bins corrected for diffraction (also affects average Nch and dN/deta)



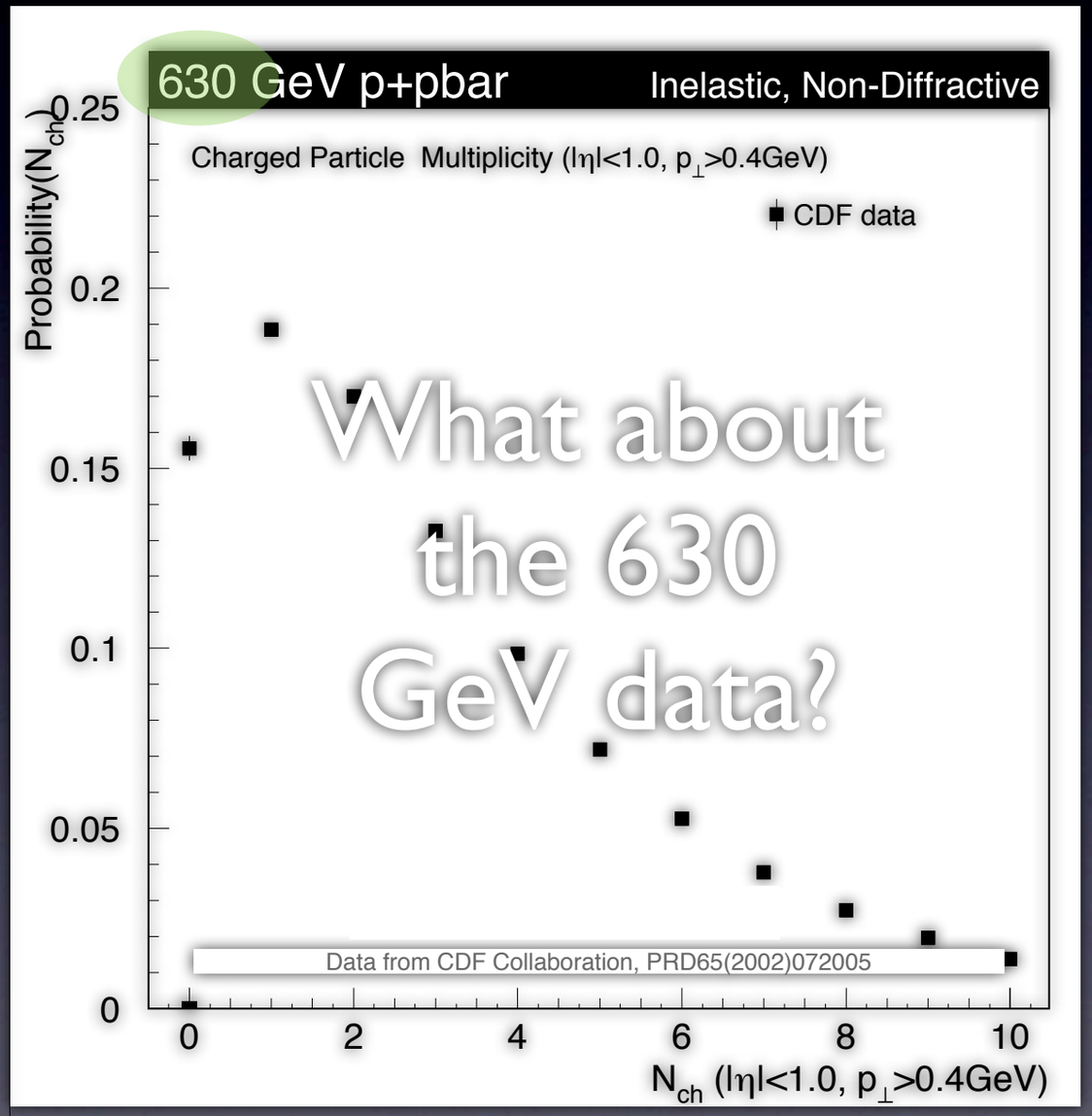
Low Multiplicities: Correcting for Diffraction

- CDF Run-II Data
  - Corrected to pT>0.4 GeV instead of full PS: less model dependence
  - First few bins corrected for diffraction (also affects average Nch and dN/deta)



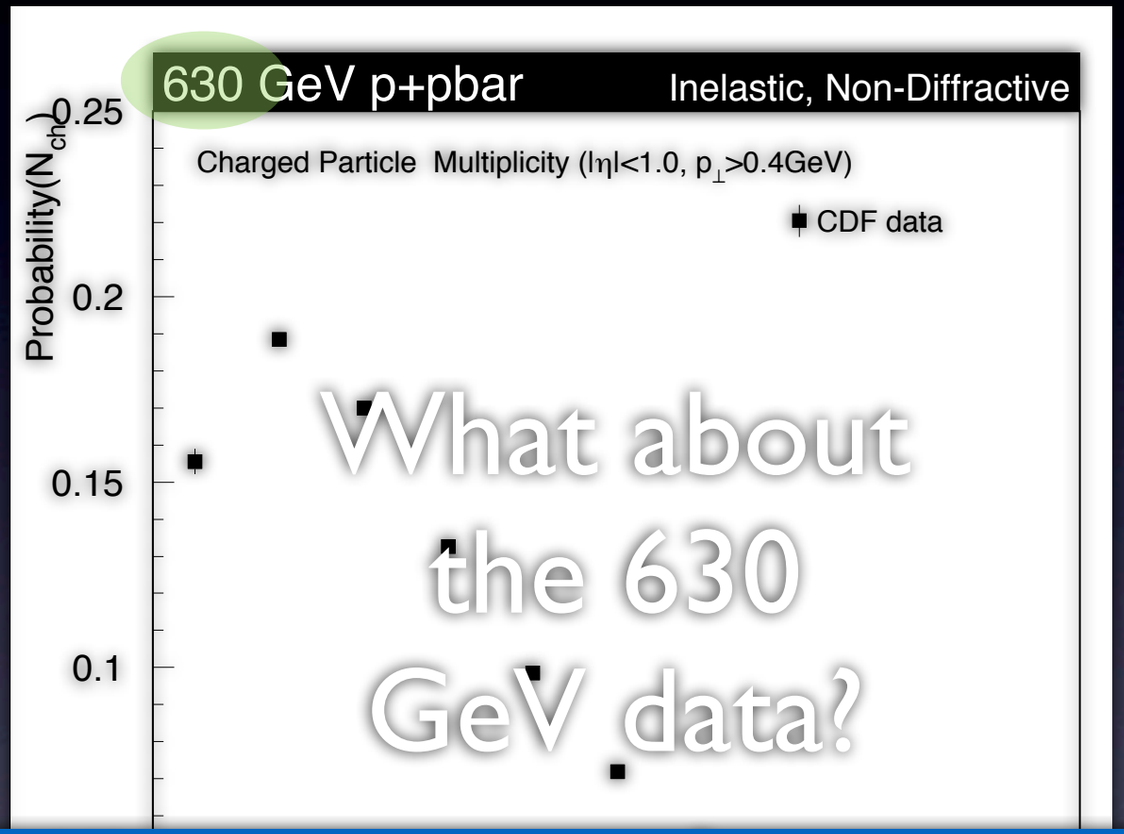
Low Multiplicities: Correcting for Diffraction

- CDF Run-I Data
  - Corrected to pT>0.4 GeV instead of full PS: less model dependence
  - First few bins corrected for diffraction (also affects average Nch and dN/deta)



Low Multiplicities: Correcting for Diffraction

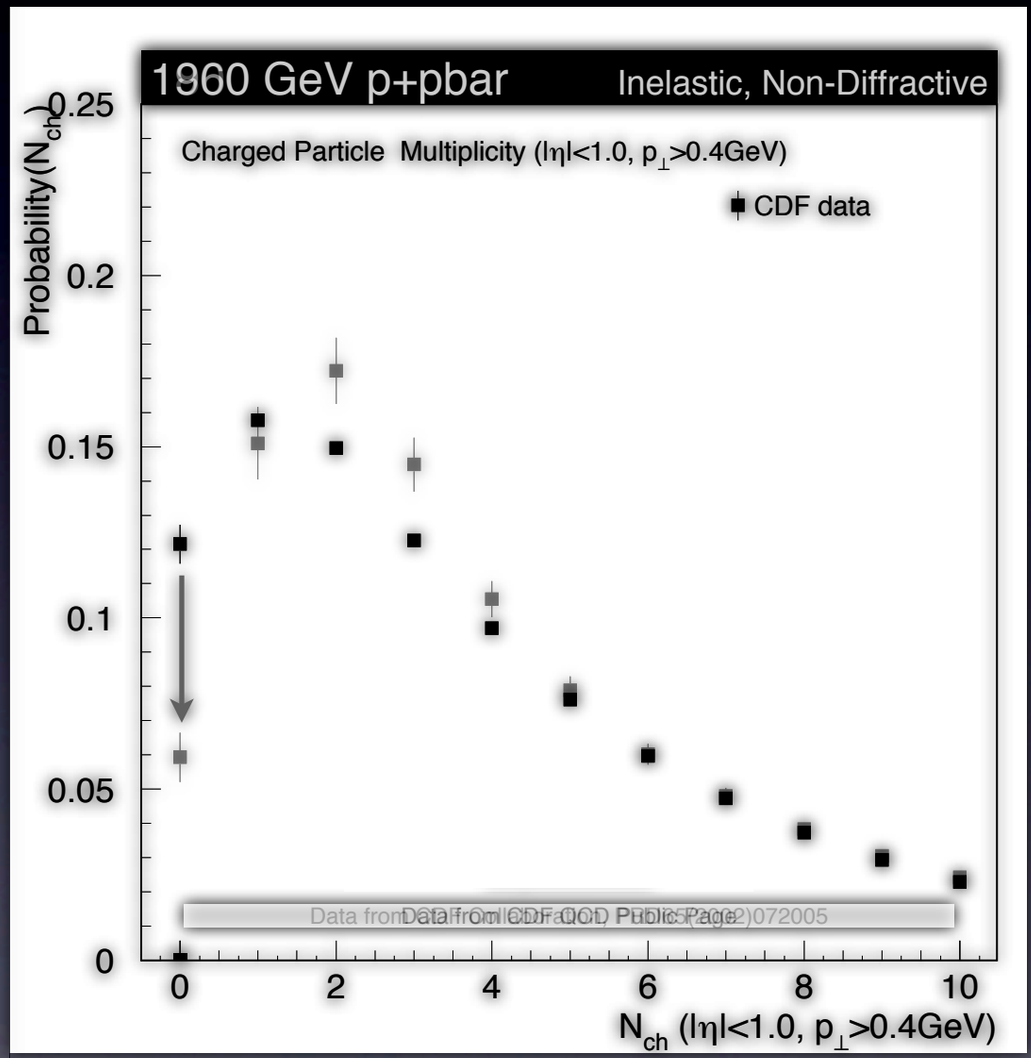
- CDF Run-I Data
  - Corrected to pT>0.4 GeV instead of full PS: less model dependence
  - First few bins



LHC Measurements at 900 and 2360 GeV, with a well-defined, agreed-upon, definition of diffraction can kill this issue

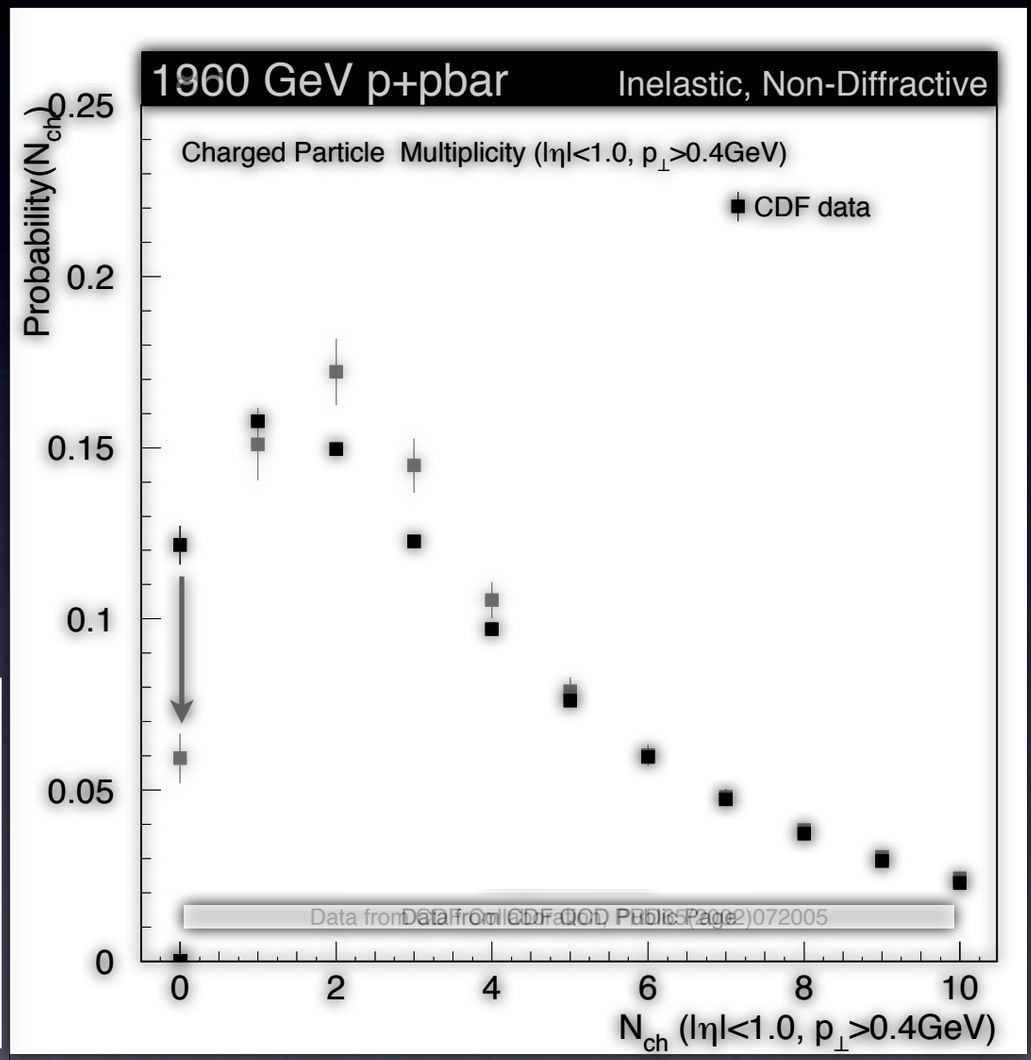
The Zero Bin

- The most problematic is the zero bin: *the event was triggered, but no fiducial tracks*
  - *E.g, was it a diffractive event with no tracks, or an inelastic non-diffractive event, with no tracks? Or … ?*



The Zero Bin

- The most problematic is the zero bin: *the event was triggered, but no fiducial tracks*
  - *E.g, was it a diffractive event with no tracks, or an inelastic non-diffractive event, with no tracks? Or … ?*



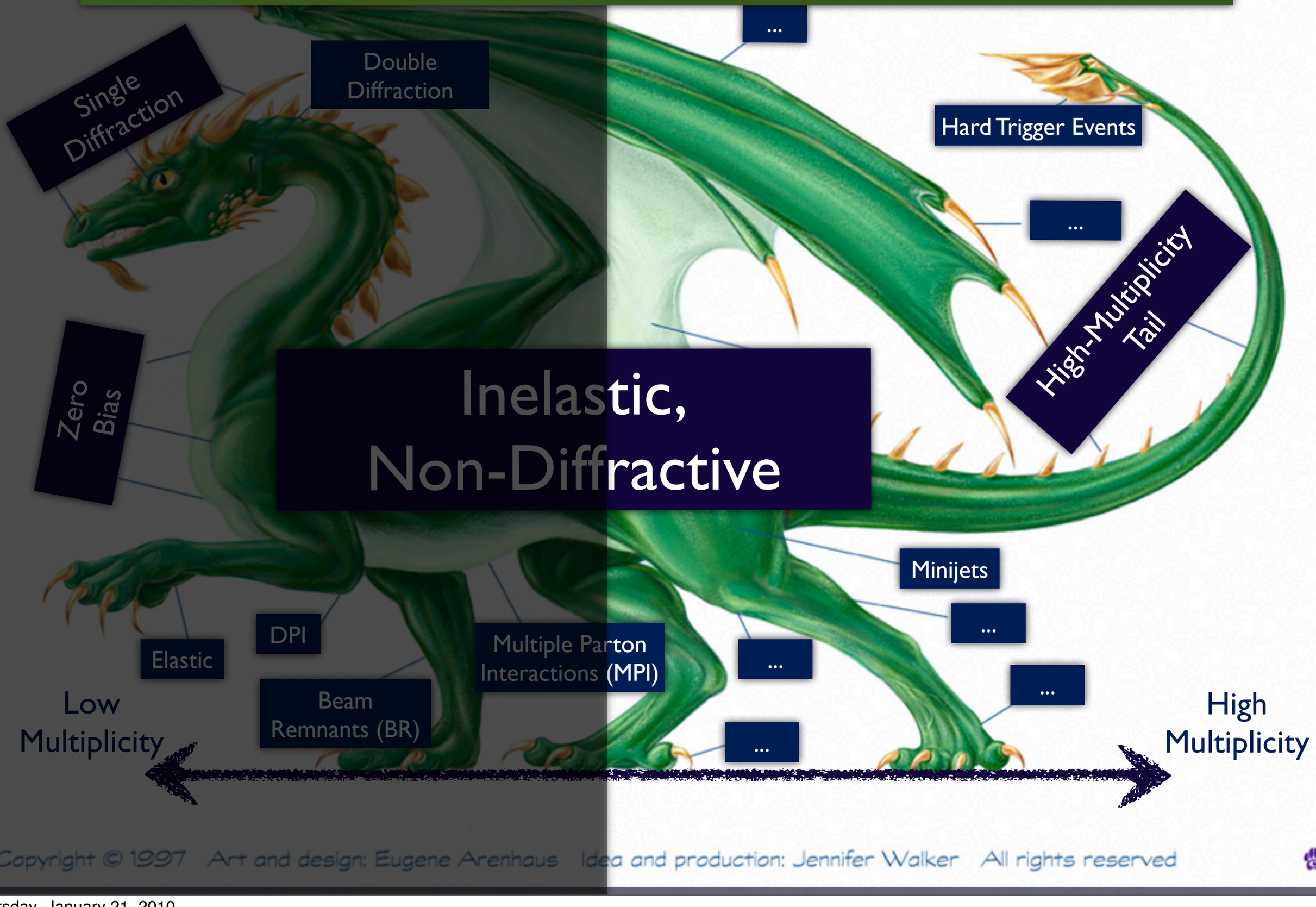
Predictions for Mean Densities of Charged Tracks

	$\frac{\langle N_{\rm ch}\rangle\,\vert_{N_{\rm ch}\geq 0}}{\Delta\eta\Delta\phi}$	$\frac{\langle N_{\rm ch}\rangle\,\vert_{N_{\rm ch}\geq 1}}{\Delta\eta\Delta\phi}$	$\frac{\langle N_{\rm ch}\rangle\,\vert_{N_{\rm ch}\geq 2}}{\Delta\eta\Delta\phi}$	$\frac{\langle N_{\rm ch}\rangle\,\vert_{N_{\rm ch}\geq 3}}{\Delta\eta\Delta\phi}$
LHC 10 TeV	0.40 ± 0.05	0.41 ± 0.05	0.43 ± 0.05	0.46 ± 0.06
LHC 14 TeV	0.44 ± 0.05	0.45 ± 0.06	0.47 ± 0.06	0.51 ± 0.06

PS, Perugia Proceedings, arXiv:0905.3418 [hep-ph]

Redefine the event sample to include at least one fiducial track?

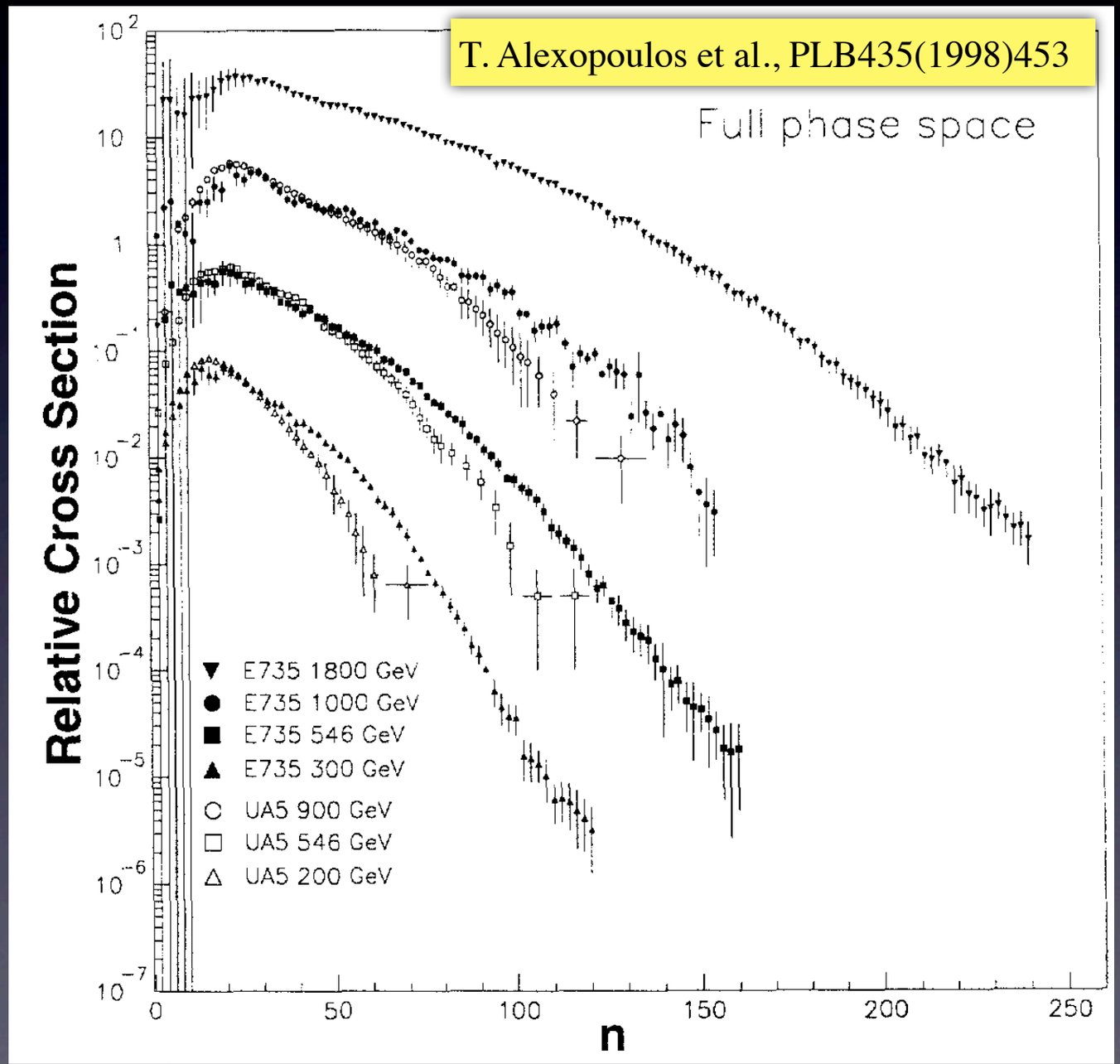
Issues at High Multiplicity



Inelastic, Non-Diffractive

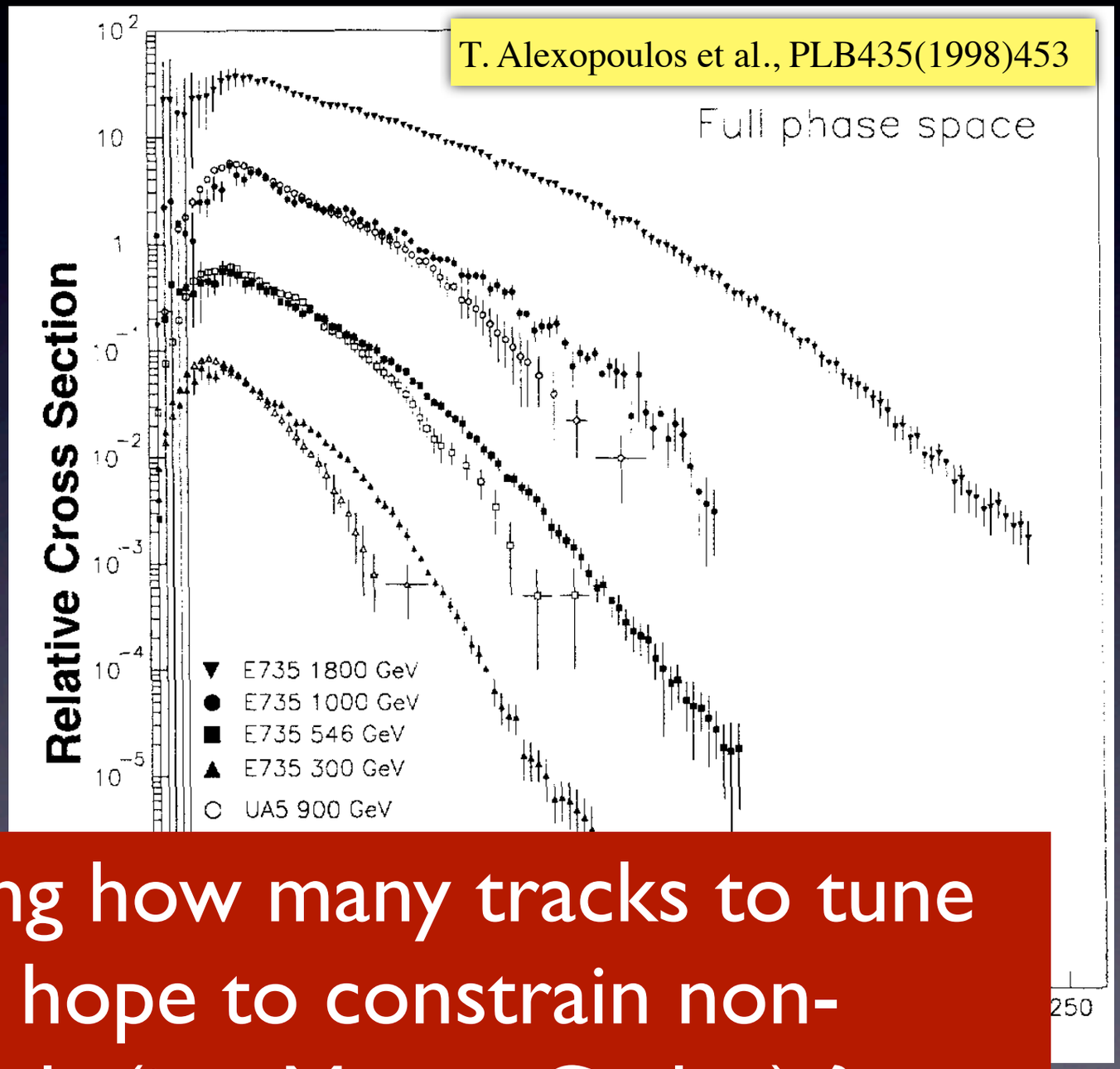
High Multiplicities: An Unresolved Question

- UA5 at 200, 546, and 900 GeV
- E735 at 300, 546, 1000, and 1800 GeV
- Mutually Inconsistent over *Entire Range*



High Multiplicities: An Unresolved Question

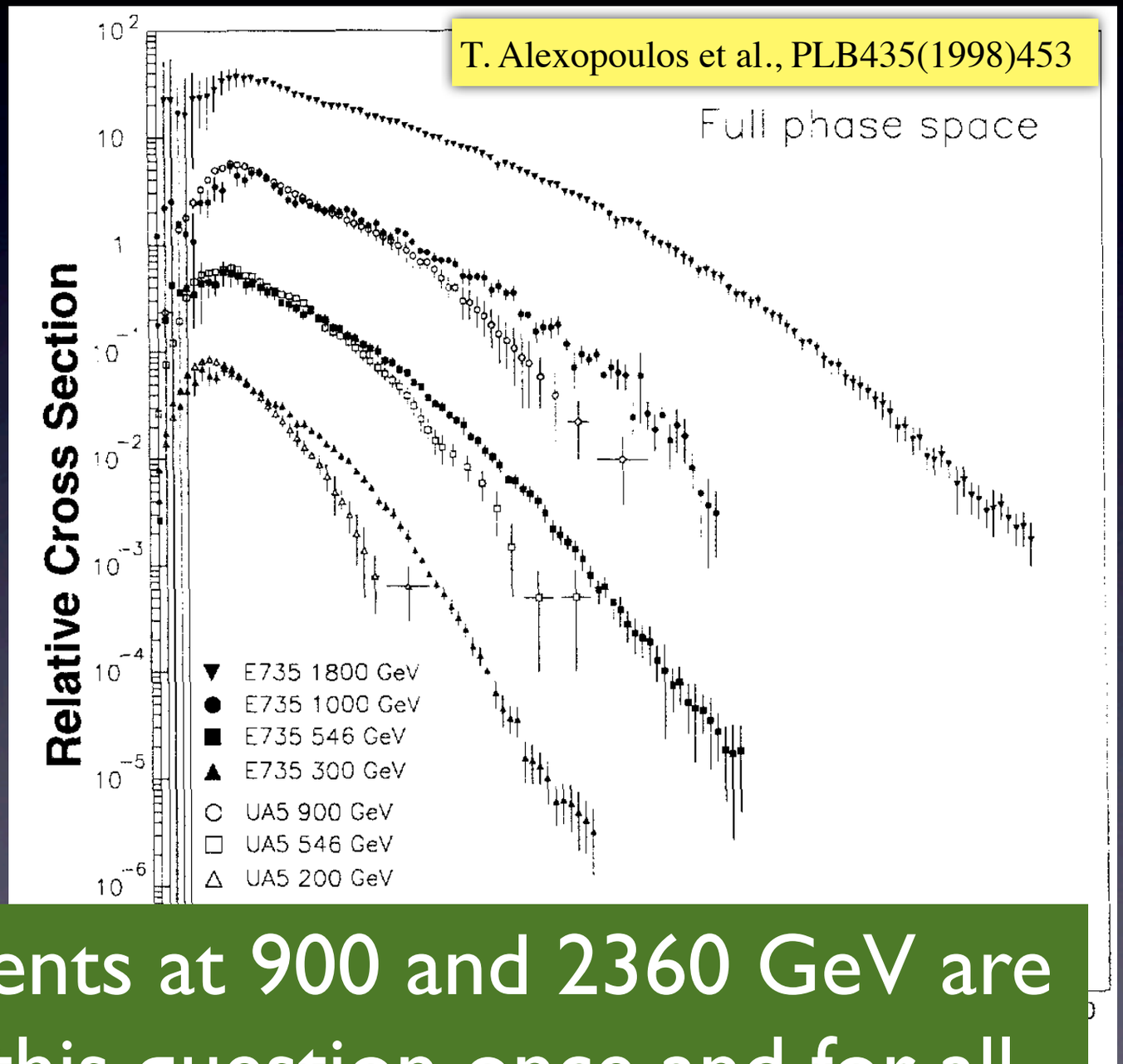
- UA5 at 200, 546, and 900 GeV
- E735 at 300, 546, 1000, and 1800 GeV
- Mutually Inconsistent over *Entire Range*



Without even knowing how many tracks to tune to, how could we hope to constrain non-perturbative models (i.e., Monte Carlos) ?

High Multiplicities: An Unresolved Question

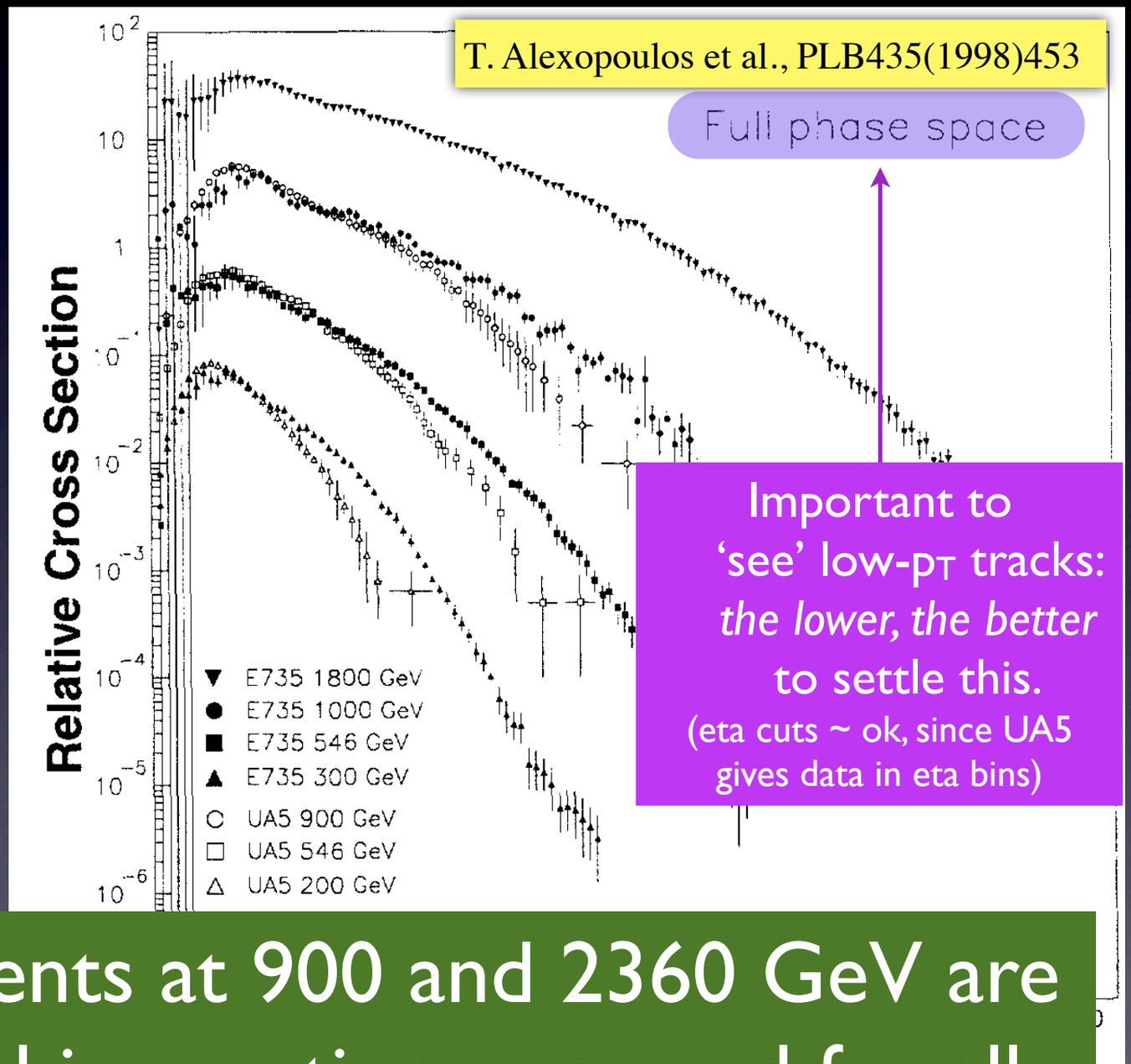
- UA5 at 200, 546, and 900 GeV
- E735 at 300, 546, 1000, and 1800 GeV
- Mutually Inconsistent over *Entire Range*



Again: LHC Measurements at 900 and 2360 GeV are *the only way* to settle this question once and for all

High Multiplicities: An Unresolved Question

- UA5 at 200, 546, and 900 GeV
- E735 at 300, 546, 1000, and 1800 GeV
- Mutually Inconsistent over *Entire Range*



Again: LHC Measurements at 900 and 2360 GeV are *the only way* to settle this question once and for all

Fragmentation

- Normal MC Tuning Procedure:
  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)

Fragmentation

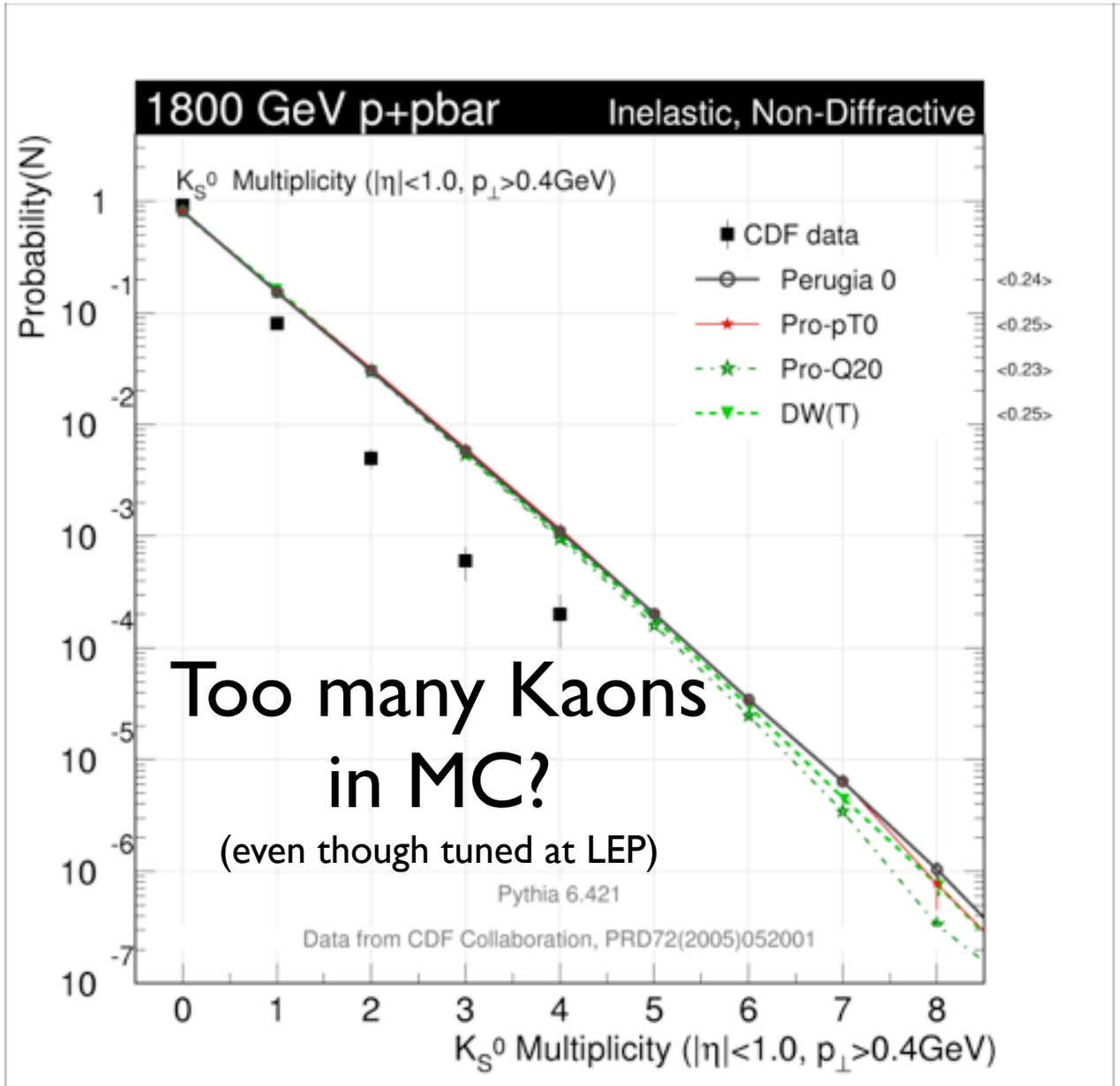
- Normal MC Tuning Procedure:
  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)
  - But pp/ppbar is a very different environment, at the infrared level!

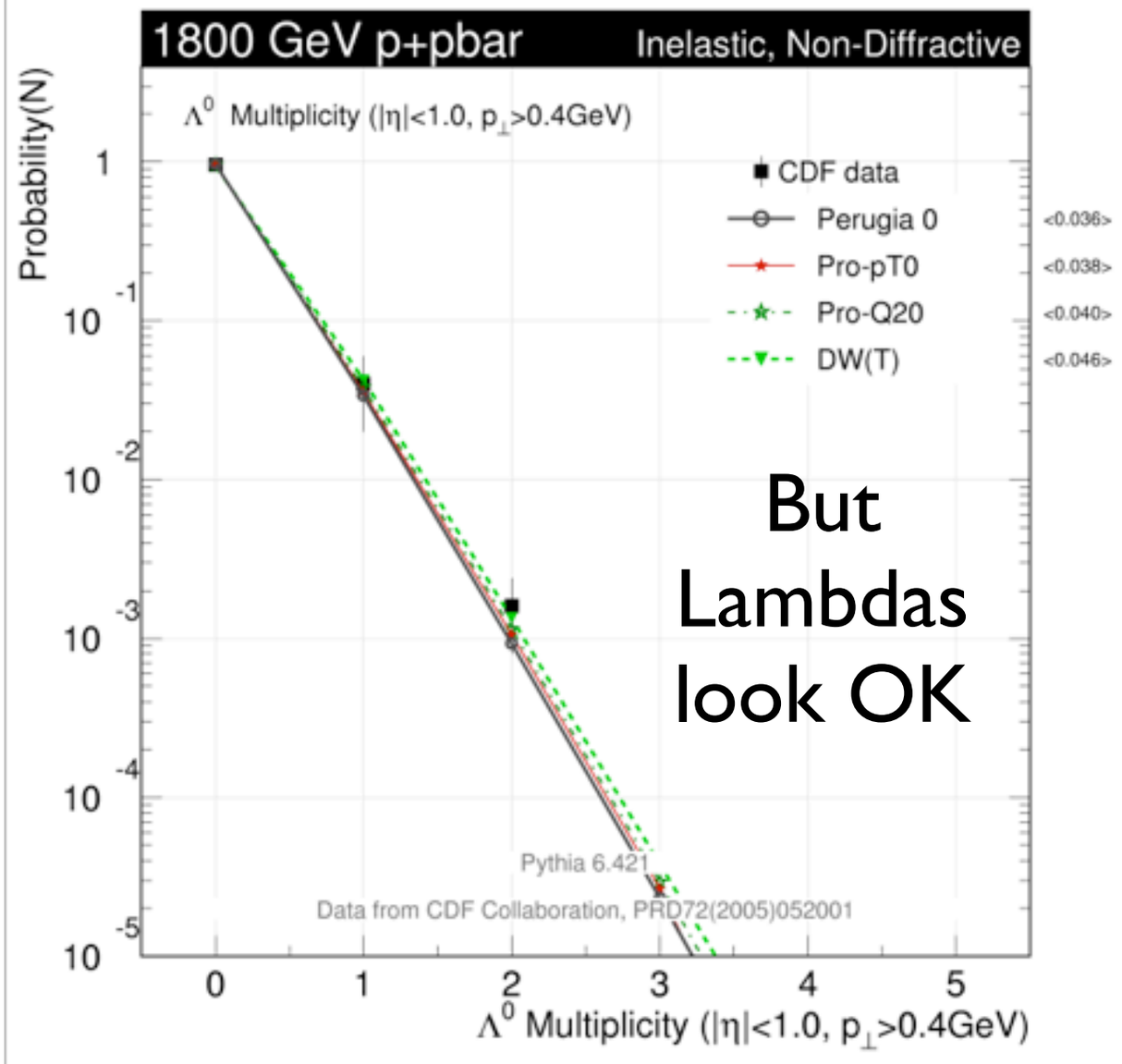
Fragmentation

- Normal MC Tuning Procedure:
  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)
  - But pp/ppbar is a very different environment, at the infrared level!

- Check fragmentation *in situ* at hadron colliders
  - *N* and p_T spectra (and *x* spectra normalized to 'jet'/minijet energy?)
    Identified particles highly important to dissect fragmentation

The Kaon Problem

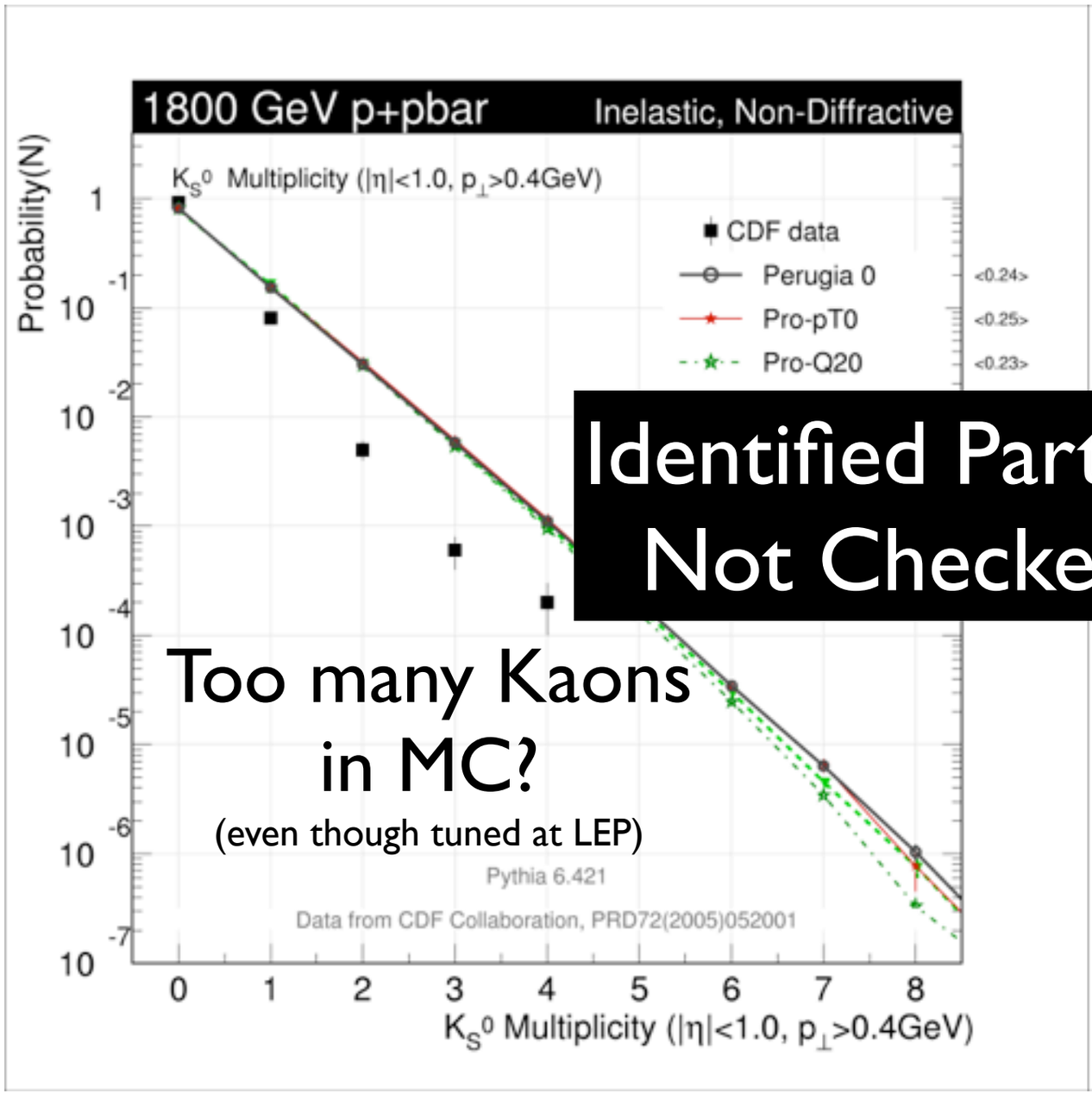




http://home.fnal.gov/~skands/leshouches-plots

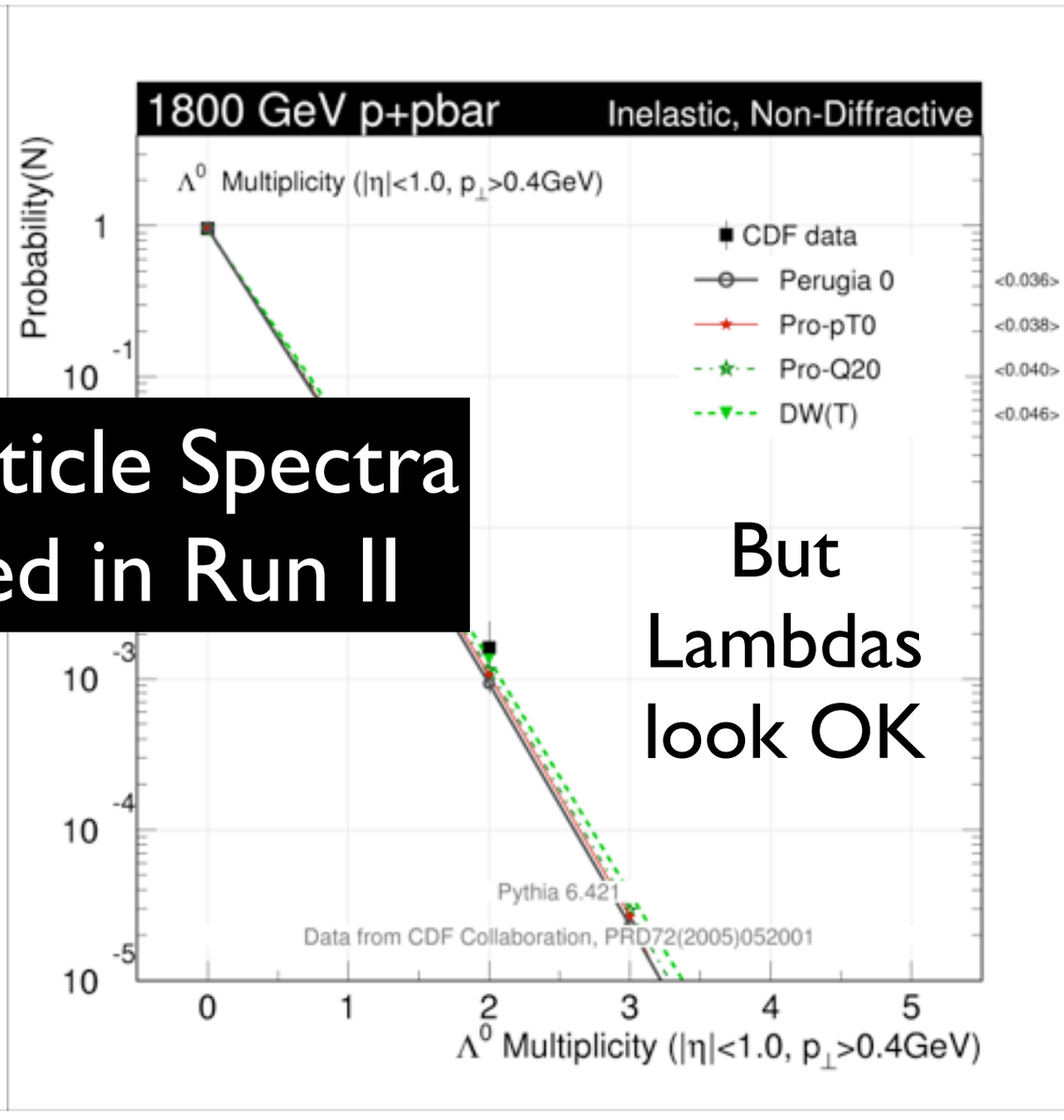
PS, fermilab-conf-07-706-t, in arXiv:0803.0678 [hep-ph]

The Kaon Problem



Too many Kaons in MC?

(even though tuned at LEP)



But Lambdas look OK

Identified Particle Spectra Not Checked in Run II

http://home.fnal.gov/~skands/leshouches-plots

PS, fermilab-conf-07-706-t, in arXiv:0803.0678 [hep-ph]

Fragmentation

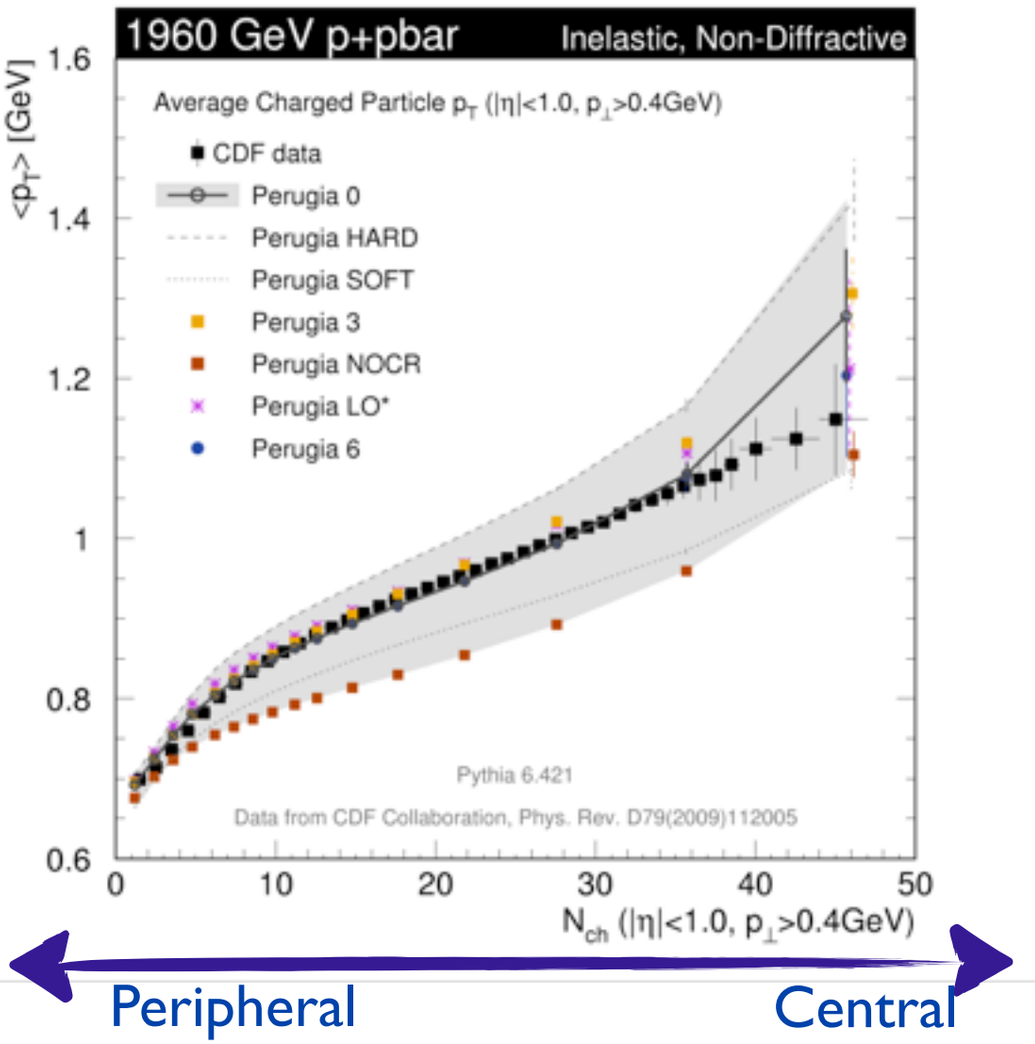
- Normal MC Tuning Procedure:
  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)
  - But pp/ppbar is a very different environment, at the infrared level!

- Check fragmentation *in situ* at hadron colliders
  - *N* and p_T spectra (and *x* spectra normalized to 'jet'/minijet energy?) **Identified particles** highly important to dissect fragmentation
  - (How) do the spectra change with (pseudo-)rapidity? (different dominating production/fragmentation mechanisms as fct of rapidity? E.g., compare LHCb with central?)
  - How do they change with event activity? (cf. heavy-ion ~ central vs peripheral collisions)

Change with Event Activity

- One (important) example: $\langle p_T \rangle (N_{ch})$

http://home.fnal.gov/~skands/leshouches-plots



The p_T spectrum becomes harder as we increase N_{ch}.

Important tuning reference (highly non-trivial to describe correctly)

(Color reconnections, string interactions, rescattering, collective flow in pp, ...?)

Fragmentation

- Normal MC Tuning Procedure:
  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)
  - But pp/ppbar is a very different environment, at the infrared level!

- Check extrapolation to forward region
  - Subir's synergy with Cosmic Ray Fragmentation
  - 'New' Physics: collective effects, multiple scatterings, low-x evolution, BFKL, ..., but central region remains important testing ground

(Additional Observables)

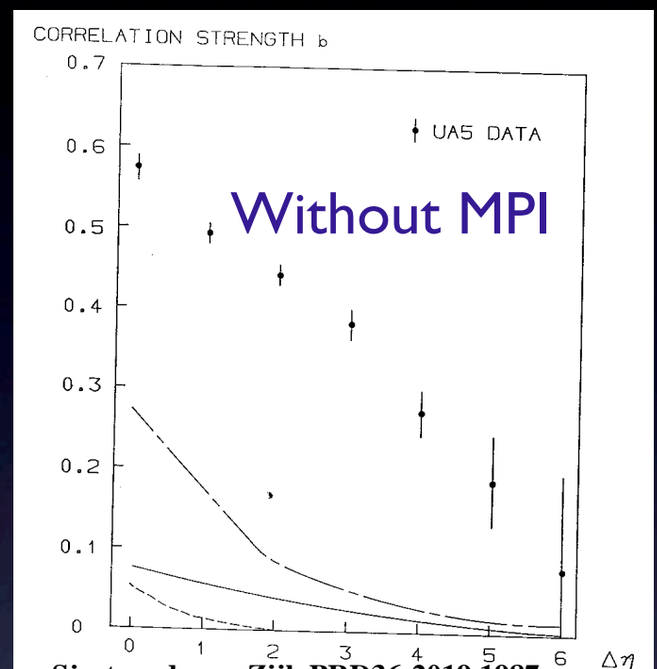
- **Particle-Particle Correlations** probe fragmentation beyond single-particle level. E.g.,:
  - A baryon here, where's the closest antibaryon?
    - + Is the Baryon number of the beam carried into the detector?
  - A Kaon here, where's the closest strange particle?
    - + Multi-Strange particles. Over how big a distance is the strangeness 'neutralized'?
  - Charge correlations. Special case: is the charge of the beam carried into the detector?

Radiation vs MPI

- What is producing the tracks?
  - Is it **Radiation**? (tends to produce partons close in phase space)
  - Or is it **MPI**? (partons going out in opposite directions)
  - Or is it soft production between the **remnants**?
- Probing long- vs short-distance correlations can tell us!
  - E.g., forward-backward correlation, *b*

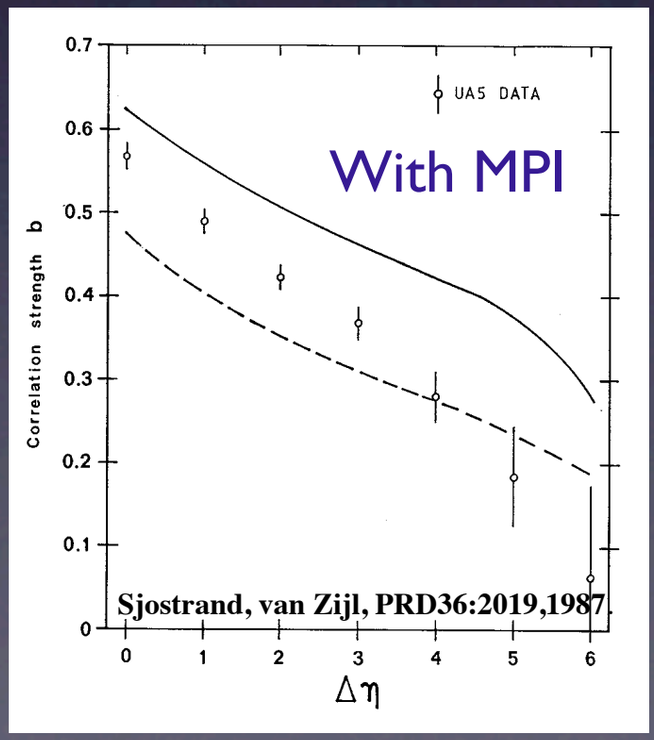
Radiation vs MPI

- What is producing the tracks?
  - Is it **Radiation**? (tends to produce partons close in phase space)
  - Or is it **MPI**? (partons going out in opposite directions)
  - Or is it soft production between the **remnants**?
- Probing long- vs short-distance correlations can tell us!
  - E.g., forward-backward correlation, *b*



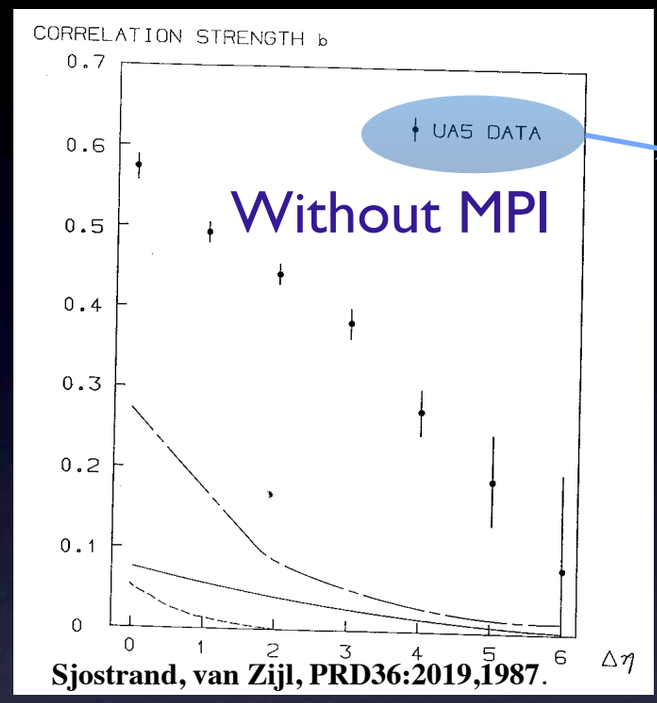
Sjostrand, van Zijl, PRD36:2019,1987.

$$b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle^2}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$



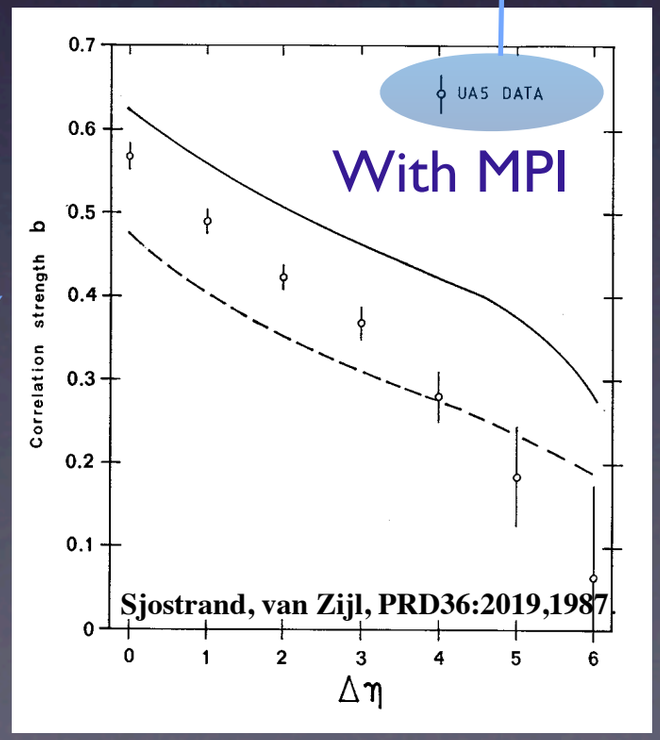
Radiation vs MPI

- What is producing the tracks?
  - Is it **Radiation**? (tends to produce partons close in phase space)
  - Or is it **MPI**? (partons going out in opposite directions)
  - Or is it soft production between the **remnants**?
- Probing long- vs short-distance correlations can tell us!
  - E.g., forward-backward correlation, *b*



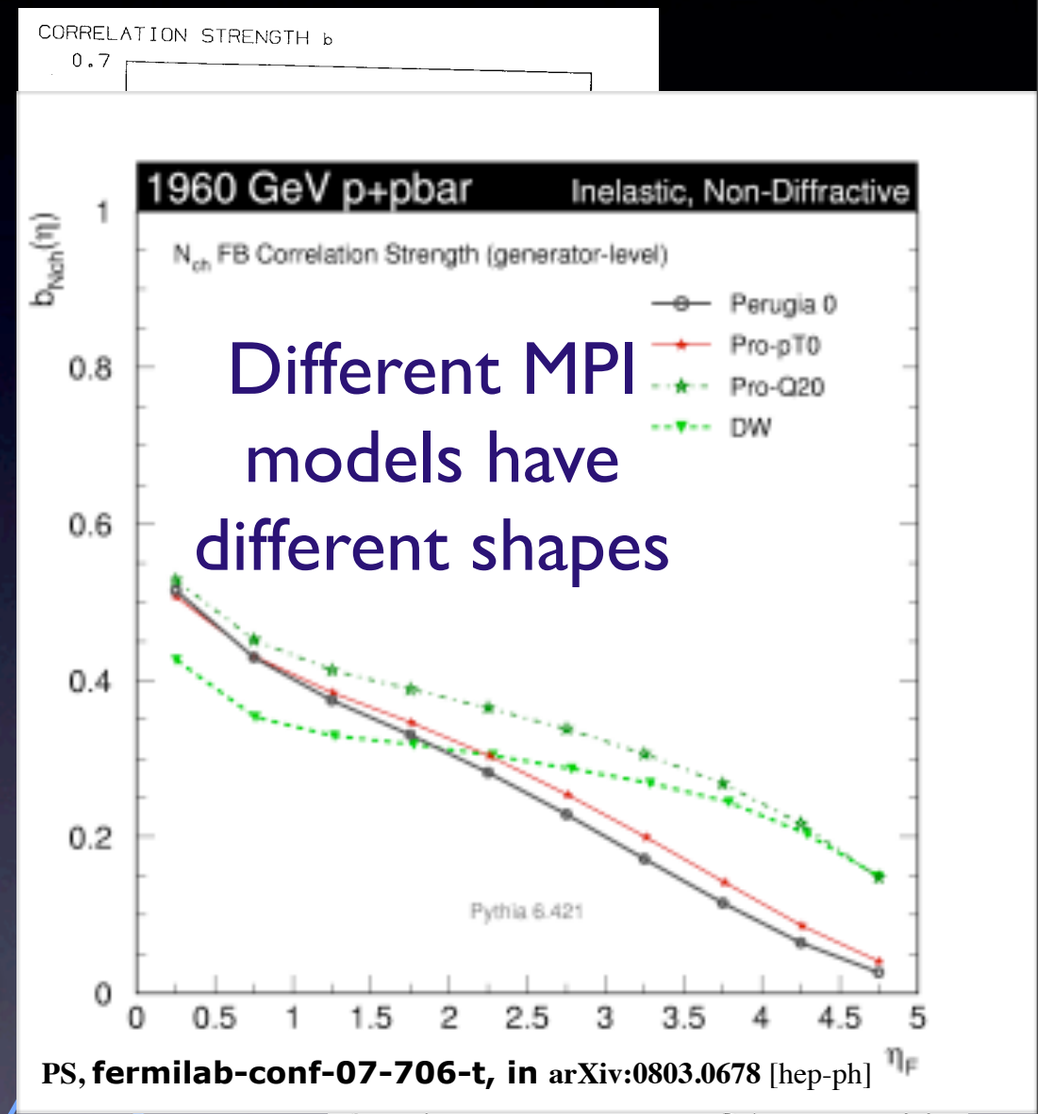
b Not measured at Tevatron

$$b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle^2}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$

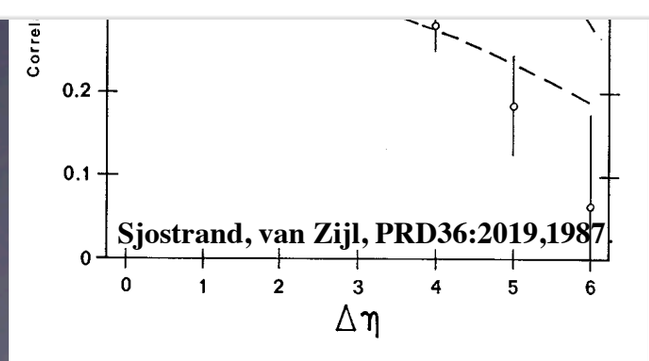


Radiation vs MPI

- What is producing the tracks?
  - Is it **Radiation**? (tends to produce partons close in phase space)
  - Or is it **MPI**? (partons going out in opposite directions)
  - Or is it soft production between the **remnants**?
- Probing long- vs short-distance correlations can tell us!
  - E.g., forward-backward correlation, *b*



$$b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle^2}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$



Summary

- The Low-Energy LHC runs offer a unique possibility to settle important business
- These are questions faced by every person (within or outside experiments) trying to constrain ('tune') physics models
- In a broader context, they concern our *knowledge* of nature